USBM Contract No. HO122026

SURVEY OF ELECTROMAGNETIC AND SEISMIC NOISE RELATED TO MINE RESCUE COMMUNICATIONS

VOLUME II

SEISMIC DETECTION AND LOCATION OF ISOLATED MINERS

Robert L. Lagace — Project Leader
John J. Ginty, Martyn F. Roetter, Richard H. Spencer

Special Seismic Consultants

Robert Crosson Roy Greenfield
Francis Crowley John Kuo
William Dean David Peters
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ARTHUR D. LITTLE, INC.
C-73912

USBM CONTRACT FINAL REPORT (Contract No. HO122026)
JANUARY 1974

DEPARTMENT OF THE INTERIOR
BUREAU OF MINES
WASHINGTON, D. C.

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FOREWORD

This report was prepared by Arthur D. Little, Inc., Cambridge, Massachusetts under USBM Contract No. H0122026. The contract was initiated under the Coal Mine Health and Safety Research Program. It was administered under the technical direction of the Pittsburgh Mining and Safety Research Center with Mr. Howard E. Parkinson acting as the technical project officer. Mr. Francis M. Naughton was the contract administrator for the Bureau of Mines.

This report is a summary of the work recently completed as part of this contract during the period August 1971 to December 1973. This report was submitted by the authors in January 1974.

VOLUME II

SEISMIC DETECTION AND LOCATION OF ISOLATED MINERS

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EMERGENCY AND OPERATIONAL MINE COMMUNICATIONS

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INTRODUCTION

This final report documents the work done by Arthur D. Little, Inc. (ADL) on behalf of the U.S. Bureau of Mines, Pittsburgh Mining and Safety Research Center (PMSRC), on Contract H0122026 (which began in August of 1971). Under this contract ADL provided technical assistance to the Bureau on a task basis on virtually all aspects of the Bureau's programs related to present and planned emergency and operational communications and miner location systems for underground coal mines. The work consisted of independent investigations, analyses, experiments, breadboard and prototype hardware development, workshops and technology transfer seminars on mine communications, and on-going evaluations and guidance related to the Bureau's contracted programs on electromagnetic noise, mine communications systems, and trapped miner location. This final report documents the work in two volumes, Volume I, "Emergency and Operational Mine Communications," and Volume II, "Seismic Detection and Location of Isolated Miners." The Tables of Contents of both Volumes are included in each Volume.

Phase I of the contract was devoted to performing an in-depth assessment of electromagnetic noise measurements taken by several contractors and other investigators, and then defining a new noise measurement program and instrumentation system tailored to obtain the necessary but missing noise data. These data are required for use in the design of new emergency and operational communication systems. This work, and the follow-on coordination and guidance activities of ADL on this noise measurement program in subsequent phases of the contract, are treated in Part One of Volume I.

The latter part of Phase I and part of Phase II included preliminary performance predictions related to through-the-earth electromagnetic communication systems. These predictions were based on available theoretical signal propagation results and on recently acquired noise data at several coal mines. This work is treated in Part Two of Volume I.

In Phases II, IV and V, investigations were conducted related to wire, guided-wireless and wireless communications systems for communicating with roving vehicles and personnel underground. This work is documented as follows. Part Three of Volume I treats guided wireless communications via leaky coaxial cable; Part Four treats wireless communications in mine tunnels at UHF frequencies; Part Five treats guided wireless communications down deep hoist shafts; Part Six treats aspects of trolley wire communications; and Part Seven treats a new mine pager telephone to public telephone interconnect system.

Another aspect of Phase V included tasks for providing assistance related to technology transfer seminars on mine communications and to a workshop on through-the-earth electromagnetics. Part Eight of Volume I treats this work. Under Phases II, IV, and V, ADL also provided a wide variety of short-term technical support and consulting services not discussed in the above mentioned Parts. This short-term work is treated in Part Nine of Volume I.

In Phase III of the contract, ADL performed another in-depth assessment on a compressed time schedule, to provide PMSRC with independent technical judgments regarding the potentials and limitations of seismic methods and systems for detecting and locating isolated miners. Volume II of this report is devoted entirely to the treatment of this work.

During the course of this contract we prepared over forty working memoranda, technical reports, seminar papers, and workshop summary reports, in addition to many informal memoranda and the monthly technical reports, to keep PMSRC informed of the progress and findings of our work as they developed. This final report is based on these previous memoranda and reports.

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EXECUTIVE SUMMARY

Arthur D. Little, Inc.

I. PURPOSE AND APPROACH

This Volume documents the Phase III effort on the Seismic Detection and Location of Isolated Miners on Contract H0122026 undertaken during the fall of 1972 by a task team composed of ADL staff and several seismic consultants. The team was assembled specifically to work together on complementary tasks, at an accelerated level of effort for four months, to meet the Bureau of Mines' time schedule for obtaining independent, objective, technical judgments regarding seismic methods and systems for detecting and locating isolated miners. The impetus for this work resulted from a compilation and analysis, during the first half of 1972, of new experimental data obtained from a series of in-mine field tests conducted by Westinghouse Corp.† using the CMRSS* interim seismic location system. The Bureau of Mines took advantage of the availability of these new data to reassess the potential and limitations of various seismic methods and systems, and to direct its seismic system improvement program accordingly.

ADL assisted the Bureau in this reassessment by drawing on the skills of seismic consultants from industry, universities and government, to supplement the skills of the ADL project team. The consultants were principal resources of broadly-based and detailed technical expertise in the areas of seismic signal-source and signal-propagation characteristics, natural and cultural seismic noise, seismic sensors and field instrumentation, seismic signal and data processing for detection and location, and overall seismic system utilization in the field under operational emergency conditions. Specifically, the participating consultants were: F. Crowley, Air Force Cambridge Research Laboratories; W. Dean, Teledyne Geotech, Alexandria Laboratories; R. Greenfield, Pennsylvania State University; J. Kuo, Columbia University; D. Peters and R. Crosson, University of Washington; and F. Pilotte, U.S. VELA Seismological Center. The principal ADL participants were J. Ginty, R. Lagace, M. Roetter, and R. Spencer.

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† Westinghouse Contract H0210063 with the Bureau of Mines.

* Coal Mine Rescue and Survival System.

Guidance and assistance related to the general suitability and applicability of recommended techniques and procedures to actual mine environments were provided by H. Parkinson and J. Powell of U.S. Bureau of Mines Pittsburgh Mining and Safety Research Center.

The overall objective of the Phase III effort was to perform a short intensive study to identify what could be done by seismic methods and systems, and how well, to:

- detect live signaling miners
- locate such miners to within the confines of a 600-by-600 foot section; and
- locate such miners to within a 15-foot entry width.

Both general and specific ground rules were established, with the assistance of the Bureau, to focus the study on the primary and fundamental aspects of the miner detection/location problem. The general ground rules are listed in Table 1 below for convenient reference. The specific ground rules related to the miner and his signal, the signal transmission path and noise environment, and the signal detection/location activity on the surface, are given in Part Twelve of this Volume.

Table 1

SEISMIC DETECTION AND LOCATION SYSTEM

General Ground Rules

- System hardware field suitable and rapidly deployable.
- System constrained to present state-of-the-art techniques and hardware.
- System operation from the surface.
- System self-contained in its operation and calibration.
- System capable of producing timely location estimates.
- System operation compatible with and complementary to overall rescue effort.
- Signal sources readily available and reasonable - no special devices carried by the miners.
- No wide-area search required by the surface team - likely areas for trapped miners given.
- Surface team will have benefit of mine maps.

Specific task areas, including output objectives and corresponding input components, were also defined, as outlined in Table 2, and assigned to the study participants. These ground rules and tasks allowed the project team to:

- obtain "best" estimates, based on available data, of the ability to detect and locate miners trapped beneath real mine overburdens;
- define the requirements imposed on the surface seismic system by operational field conditions for successfully executing the detection and location operations;
- assess how the above estimates are influenced by system complexity and cost; and
- determine what is still needed in terms of basic data, analyses, and experiments to improve and/or verify these estimates.

Parts Two through Six of this Volume address in detail the major output objectives of detection, arrival time estimation, location, and field utilization. Similarly, Parts Seven through Eleven treat the input components -- seismic signal source and transmission characteristics, earth models, seismic noise, signal-to-noise improvement techniques, and seismic detection/location instrumentation, which influence the ability to achieve the above output objectives. Part Twelve presents copies of the visual aids used in the initial ADL briefing given to the seismic consultants regarding the relevant background, ground rules, major problem components, and identification of specific tasks to be addressed; and those used in the ADL oral presentation of results of this study to PMSRC. The authorship of each Part is designated to appropriately acknowledge the major contributions of each seismic consultant. Consultant F. Crowley also provided key assistance to ADL in its role of overall definition, coordination, and integration of the study effort within the compressed time schedule. The following sections of this Part briefly summarize the principal findings and conclusions of the study regarding the main objectives of detection and location of isolated miners. These findings and conclusions are supported in the subsequent Parts of this Volume.

TABLE 2 TASK AREAS

INPUT COMPONENTS ↓ / OUTPUT OBJECTIVES →	DETECTION	PARAMETER ESTIMATION	LOCATION	EFFECTIVE FIELD UTILIZATION
	MAJOR INPUT COMPONENT CHARACTERISTICS AFFECTING OUTPUT OBJECTIVES			
SIGNAL SOURCES Fn of: Type : Man : Impact Area : Tunnel	• Strength • Directional and Coherence Charac. • Pulse Shape • Rep. Rate	• Strength • Directional and Coherence Charac. • Pulse Shape • Rep. Rate	• Directional Charac.	• Site Environment - Physical - Operational • Field Crew • Hardware • Deployment and Operation Procedures • Overall Rescue Operations ↓
TRANS. MEDIUM. CHARAC. Fn of: Layers (Type, Thick, Angle, etc.)	• Attenuation • Signal Modification - Freq. Response - Time Domain - Spatial Coh.	• Attenuation • Signal Modification - Freq. Response - Time Domain - Spatial Coh.	• Earth Model (Detailed)	
NOISE Fn of: Sources - Sig. Induced - Rescue Sources - Basic Bgrd. - Altered Mine - Message - System	• Spectrum Levels • Time Charac. i.e. Stationarity Impulsiveness • Spatial Coherence	• Spectrum Levels • Time Charac. i.e. Stationarity Impulsiveness • Spatial Coherence	• Noise Weighting of Parameters	
SENSORS Fn of: Depth : Coupling	• Sensitivity • Array Gain/ Directionality • Dynamic Range • Polarization	• Sensitivity • Array Gain/ Directionality • Dynamic Range • Polarization	• Array Geometry and Location	
SIGNAL PROCESSING	• Candidate Detection Methods	• Candidate Estimation Methods		
DATA PROCESSING AND COMPUTATION			• Location Algorithms • Mine Maps	

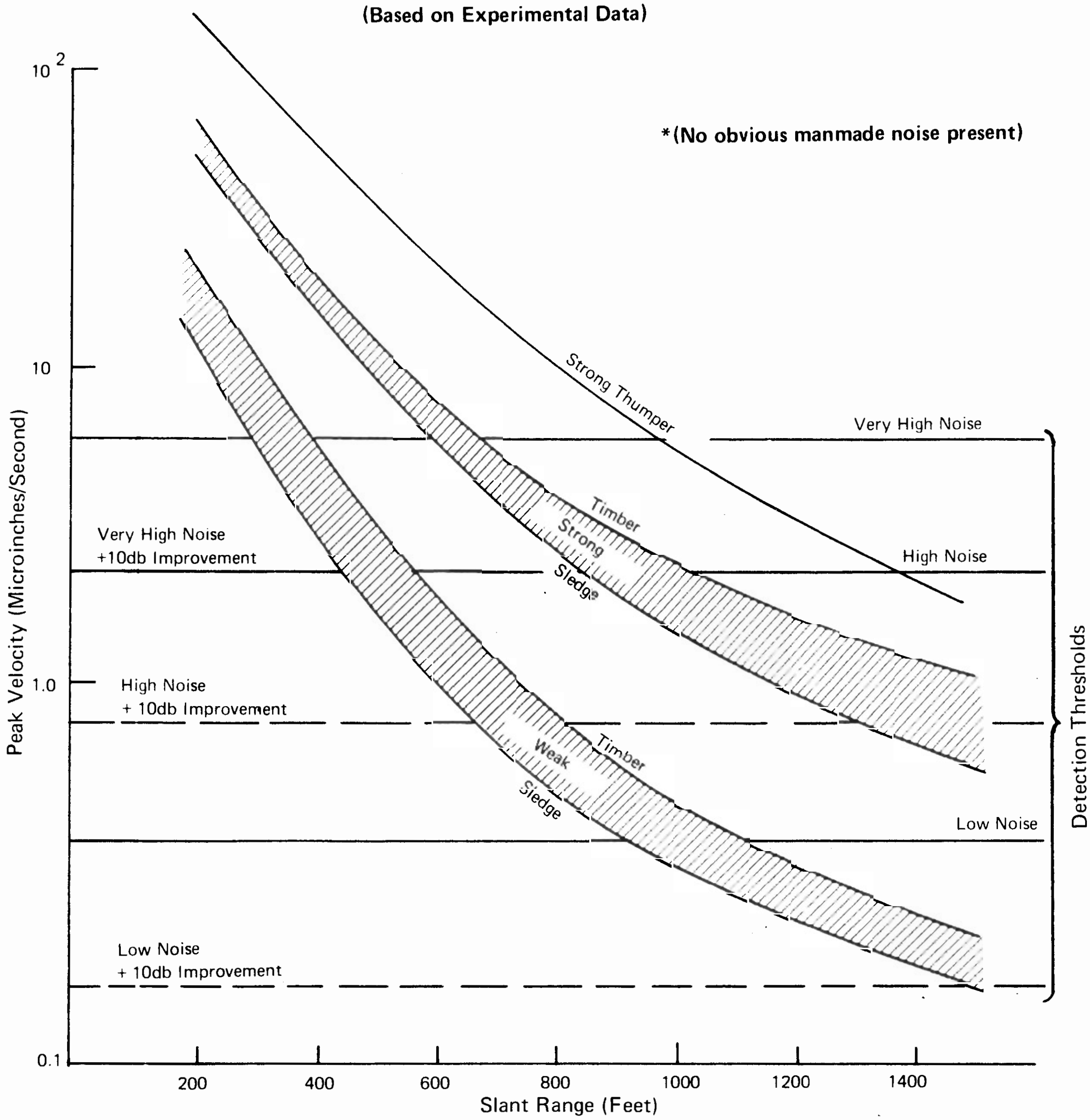
II. SUMMARY OF RESULTS

A. DETECTION OF A MINER

A surface deployed seismic system utilizing conventional signal-to-noise ratio improvement techniques can provide the capability of detecting miners signaling with timber or sledge sources, to slant ranges on the order of 1000 feet, under most natural seismic noise conditions in which no man-made noise sources are present. Under such noise conditions, these ranges should allow more than adequate coverage of typical mine sections. However, to obtain these noise conditions, surface rescue operations and activity in the vicinity of the detection area must be severely restricted and possibly prohibited. This may not be compatible with present mine rescue operations. Though more experimental noise data must be obtained and analyzed before definitive estimates can be made of the reduced detection ranges in the presence of man-made noise of the type and level present during uncontrolled rescue operations, it is highly likely that the presence of such noise will make the detection of a signaling miner impossible with a surface seismic system.

The dependence of detection range on the type of signaling source and on the levels of naturally occurring seismic noise is shown in Figure 1. Figure 1 depicts the variation of received signal strength with type of source and slant range above the source, derived from data taken at several mines. The horizontal lines denote signal detection thresholds for three representative natural noise conditions, with and without the benefit of a conservative 10 dB improvement in signal-to-noise ratio. These natural noise conditions are based on published data taken at several locations other than above mines. Only a limited sample of suitable noise data taken above mines at quiet times was available for comparison. These noise levels at mines were not inconsistent with the more comprehensive natural noise data used.

FIGURE 1 COMPOSITE PLOT FOR ESTIMATING DETECTION RANGES UNDER NATURAL NOISE CONDITIONS*
(Based on Experimental Data)



Detection ranges are obtained by noting the intersection of the signal curves with the corresponding detection thresholds of interest in Figure 1. Noise levels and corresponding detection thresholds for uncontrolled rescue operations are expected to far exceed those for the very high natural noise condition, thereby drastically reducing detection ranges to unacceptable levels. Table 3 presents, for convenient reference, a summary of detection ranges derived from the curves of Figure 1. Table 4 summarizes those signal-to-noise improvement techniques judged most and least useful for detecting and locating isolated miners.

To improve these detection range estimates and to better evaluate the utility of the signal-to-noise improvement techniques identified as most useful, a series of careful seismic noise and signal strength measurements should be performed in Eastern coal mining regions by field crews well-experienced in seismic and geophysical field work. This work should be supported by theoretical analyses to better understand the generation and propagation behavior of signals produced by practical signaling sources available to miners during emergencies in coal mines. Detailed treatments on detection range estimation and signal-to-noise improvement techniques are found in Parts Two and Ten, respectively.

B. LOCATION OF A MINER

The above described detection process, being inherently limited to slant ranges on the order of 1000 feet, in itself provides a coarse location of a trapped miner that in many cases may be sufficient to direct the efforts of a rescue team. However, should greater accuracy be required, location of a miner to within a section is a realistic objective. In fact, location accuracies to within 100 feet for miners down to depths of 1000 feet appear attainable with surface deployed systems, but only when the required conditions are met. Namely, when an adequate seismic representation (model) of the earth beneath the surface seismic system is available, the depth of the miner is known from a good mine map, and as in the case of detection, the surface rescue operation and activity

TABLE 3
MAXIMUM SLANT RANGES (In Feet) FOR DETECTION-UNDER NATURAL NOISE CONDITIONS**

Source	Low Noise		High Noise		Very High Noise	
	W/O-S/N I*	W-S/N I	W/O-S/N I	W-S/N I	W/O S/N I	W-S/N I
Strong Thumper	>2000	>2000	1400	>2000	950	1400
Strong						
Timber	>2000	>2000	1050	>1500	650	1050
Sledge	>1500	>2000	900	1250	550	900
Weak						
Timber	1100	>1500	550	800	375	550
Sledge	900	>1400	450	625	300	450

* W/O - S/N I = Without 10dB Signal-to-Noise Improvement
W - S/N I = With 10dB Signal-to-Noise Improvement

** No obvious manmade noise sources

Table 4

SIGNAL-TO-NOISE IMPROVEMENT TECHNIQUES

Most Useful

For Detection	For Arrival Time Estimation
. Bandpass Filtering	. Same as for Detection
. Burial of Sensors	. Summing (Stacking) of Repeated Signals
. Subarrays:	
- size optimization	
- delayed or direct sum	
- weighted sum	

Least Useful

For Detection and Arrival Time Estimation

- Remode Processing
- Linear Phase Filtering of Multicomponent Data
- Matched Filtering
- Multichannel Maximum Likèlihood Array Processing
- Multichannel Wiener Filtering
- Single and Multichannel Prediction Error Filtering

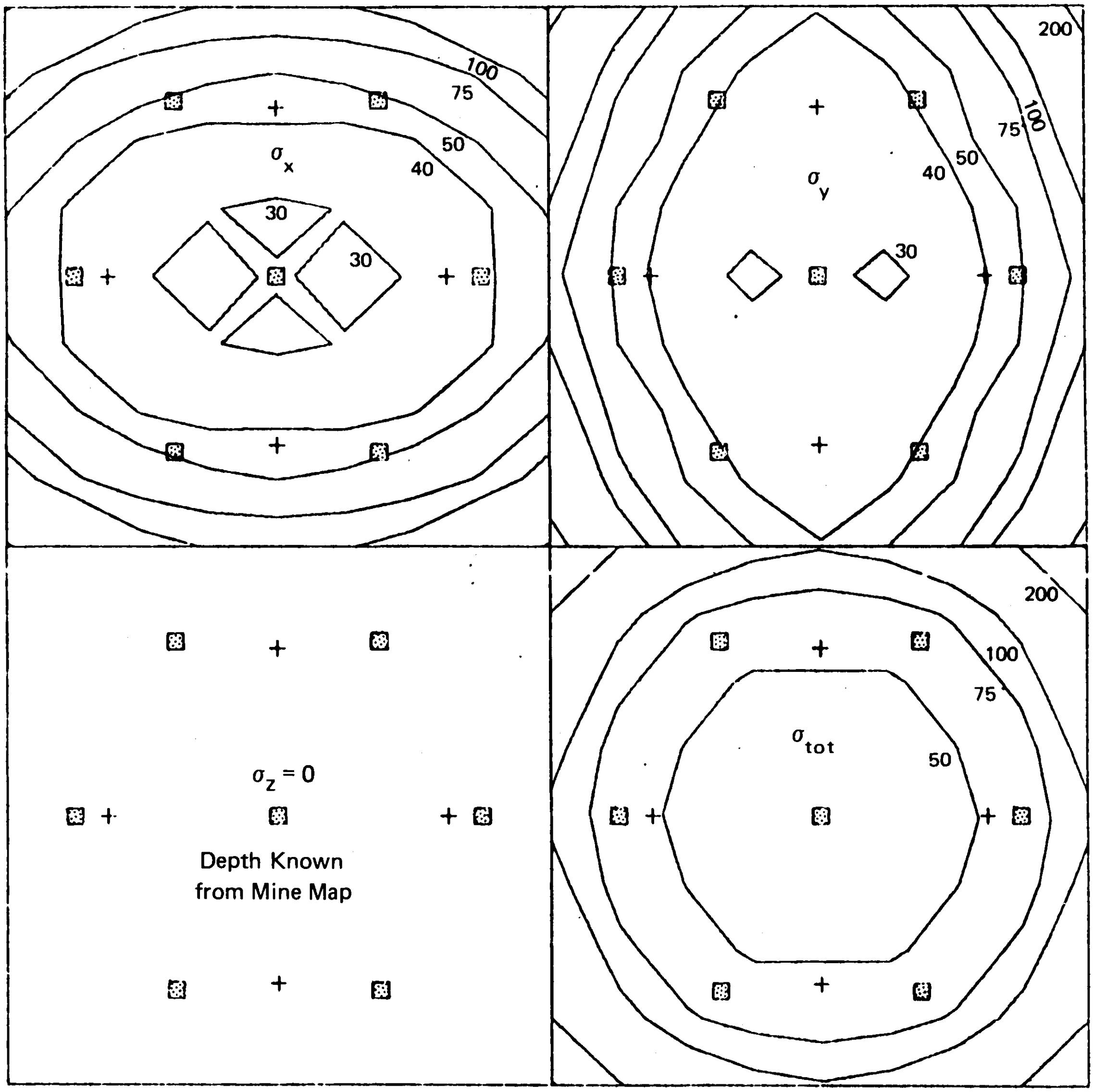
in the vicinity of the location area has been severely restricted and possibly prohibited, which again may not be compatible with present rescue operations. Indeed, for accurate miner location, signals will have to be received on several seismometers surrounding the miner's location, and signal-to-noise ratios well in excess of those for detection will also be required to adequately estimate to sufficient accuracy the signal arrival times needed for computing location coordinates. Specifically, the above estimate of location accuracy applies only to favorable, controlled conditions:

- when the signals are strong enough to allow arrival times to be measured to within 1-5 milliseconds, and
- when the earth at the local mine site can be adequately represented by a set of laterally homogenous horizontal layers with different seismic velocities, and these parameters can be specified to within about 5% by refraction surveys from the surface.

Though available geological information tends to support the reasonableness of the type of seismic earth model assumed, data from refraction surveys performed directly over representative coal mines, together with controlled location experiments using strong signal sources, are still needed to confirm the general applicability of this kind of model. Figure 2 is an example of the location error contour maps generated during the study to form a basis for drawing conclusions on attainable location accuracy with surface seismic arrays. These contours are based on an error analysis applied to the well-established location method of non-linear, least squares iterative inversion. The contours in each square represent the estimated standard location errors in x, y, and z (one standard deviation, σ, of a normal distribution) for a source so located relative to the array geometry.

The location results indicate that earth model errors of 5% will be the dominant contributors to miner location errors when arrival time errors fall between 1-5 milliseconds, but that arrival time errors become the major contributors and seriously degrade location accuracy when these

FIGURE 2 EXAMPLE OF LOCATION ERROR CONTOUR MAPS



4 Layer Model
$\sigma_v = 5\%$
$\sigma_t = .001$

σ_{tot}min. = 41.0

ERROR CONTOURS IN FEET
SOURCE DEPTH – 600 FEET
7-ELEMENT HEXAGONAL ARRAY

timing errors reach 15-20 milliseconds. Errors of this magnitude can be introduced by low signal-to-noise ratios and by the variable thickness of low-velocity weathered layers under different seismometers in the location array. Hence it is important to account for such sources of large timing errors in the field.

The further objective of directly locating a signaling miner to within an entry width with a surface seismic system appears to be an unrealistic goal. Only under the most favorable but improbable circumstances, namely, noise conditions similar to or better than those described above, and an even more accurate representation of the earth or shallower mine depth (300 feet or less), do location accuracies of about 30 feet appear attainable. With the aid of a good mine map, these accuracies could allow the surface team to identify the entry in which the miner is located. However, the only method that is likely to produce accuracies of this order in practice is a more costly reference event method. This method relies on the prior calibration of the seismic properties of the earth over the mine by initiating and recording seismic reference events on a regular periodic basis. Detailed treatments of the location algorithms examined in this study; namely, non-linear least squares iterative inversion, Westinghouse program "Miner", and reference events, together with the suggestion of even more advanced algorithms that allow iterative improvement of the earth model as well as the predicted location, are found in Parts Three, Four, Five and Seven.

C. FIELD UTILIZATION

The nature of mine emergencies, the experience gained with the present interim seismic location system, and applicable experience of our consultants related to the deployment of small, highly mobile, operational seismic teams, lead to several guidelines and recommendations regarding the field utilization of the seismic equipment and the composition of the seismic team. The seismic system should be transportable and deployable in various configurations, depending on the mine location and on the needs of the detection and/or location operations. The range of field requirements extend from the need for simple detection processes in quiet remote locations, to complex detection and location processes in areas of relatively easy access with unfavorable noise environments.

Therefore, the system should be configured in modular form that allows deployment in phases. For example, on notification of a mine emergency, the initial deployment could include only a simple portable detection system capable of being easily transported by commercial or private aircraft, automobile, or a small truck to the mine, and back-packed to specific locations over the mine workings if necessary. This simple detection system would be composed of a small array subsystem, an array control unit, an oscilloscope, and possibly a multichannel strip chart recorder. These units are sufficient to obtain not only initial detection of miners, but also first-order location of these miners in the vicinity of the sites chosen for initial investigation. A more comprehensive, easily transportable, van processing center and additional subsystems could be deployed shortly thereafter, or as required by the particular emergency situation.

The equipment must be made simple, weather tight, rugged, modular, and temperature insensitive. In addition, because the location of miners requires calibrated signals and test and repair facilities may not be readily available, calibration and check-out of the system must be easy to do on site. Since power may not be available, battery operation is a must for the portable field equipment. Furthermore, because emergency conditions require quick response, not only must the equipment be quickly and easily deployable at the site, but speed in the acquisition and processing of the seismic data is essential once the system has been deployed. Indeed, overall processing times of received data should be measured in minutes rather than hours. Table 5 summarizes some of the important hardware requirements for a flexible, fieldable seismic detection and location system. These requirements can be met by appropriately integrating and packaging present off-the-shelf components and equipment.

Table 5

HARDWARE REQUIREMENTS FOR SEISMIC DETECTION/LOCATION SYSTEM

- Compact light-weight, rugged, modular, proven hardware
- Simple and easily deployable
- Combination vertical seismometer/amplifier unit capable of burial
- Water proof non-ambiguous cabling and array control unit
- Seismometer calibration device
- 12-channel tape recorder
- Multichannel hard-copy-output recorder
- Accurate, recoverable time codes on tape, or paper output
- Continuous time reference on tape, or paper output
- Selectable time base displays
- Variable filtering and gain
- Battery operation of portable subsystems
- Radio communication for crew
- Tools
- Van processing center with disk pack and mini-computer

The final essential element required to ensure the successful utilization of the system during a mine emergency is the composition and experience of the seismic team. The minimum requirement is a three-man cadre that is trained to work together under such emergency conditions, being completely familiar with all aspects of the system and its operation and each others duties. This cadre should include an operator/analyst an electrical technician, and a field technician. The operator/analyst will be the team chief and should also be an experienced geophysical engineer. This cadre would utilize additional but inexperienced mine personnel at the site to expedite deployment of the system. The key man of this cadre is the team chief who should also be a mature individual who is thoroughly familiar with mining operations and practices, can interface effectively with the overall resuce coordinators, and successfully direct the seismic detection/location operation in the face of confusion and possibly conflicting rescue requirements. Detailed treatment of the instrumentation and its field utilization requirements will be found in Parts Six and Eleven.

III. CONCLUDING REMARKS

As stated in the Purpose and Approach Section of this Part, the purpose of this study was to provide results to help the Bureau of Mines in the formulation of future policy and plans of action related to the detection and location of isolated miners by the application of seismic methods. In this regard, an additional question was posed by the Bureau, for consideration by the ADL seismic team during the course of this task. Namely, which of the following alternative courses of action appear to be most feasible and appropriate at this time:

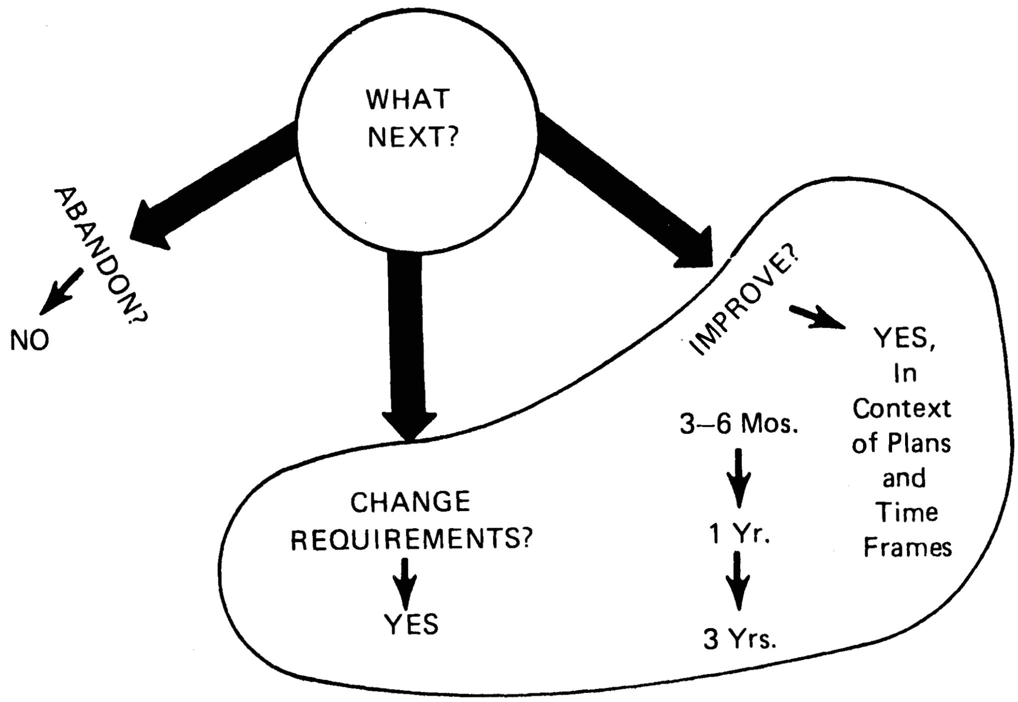
- Abandon the seismic system and rely on electromagnetic or other methods?
- Change the performance requirements of the seismic system - for example, by only requiring positive location to within the dimensions of a working section?
- Improve the system and seismic methods employed?

Figure 3 summarizes the three alternatives and the corresponding ADL responses in a graphic format. Expansions on these responses follow.

No, it would not be appropriate to abandon seismic detection and location methods at this time, in spite of their shortcomings. Until viable electromagnetic miner location equipment is developed, produced in quantity, and utilized by the mining industry, seismic methods still remain the only means presently available for detecting the presence of live signaling miners and determining their location from the surface.

Yes, it is definitely feasible and appropriate to change the performance requirements for a seismic system, particularly regarding the required accuracy of location. Location accuracies to within one or two coal pillars, and even to within dimensions of a working section, when used in conjunction with a good mine map, will be extremely valuable and in many cases, be more than sufficient to direct the efforts of both in-mine rescue teams and surface drilling crews. However, it should be remembered that rescue operations and activity in the vicinity of the location area may have to be severely restricted, and possibly prohibited temporarily, to achieve these location results.

FIGURE 3 ALTERNATIVES



Yes, it is definitely required, feasible, and appropriate to improve the system and seismic methods employed to detect and locate isolated miners. However, the type and extent of these improvements need to be determined by the Bureau in the context of its overall plans and associated time frames related to its miner location programs. In this regard, the Bureau will find that some quick-fix and minor improvements will be suited to 3-6 month schedules, while others that are major or that require additional fundamental investigations may require schedules of 1 to 3 years.

Each of the improvements referred to above will require investments of one kind or another that will impact on both cost and performance. Table 6 briefly summarizes the expected impact on system performance and cost for several possible kinds of investments. Finally, in order to more accurately estimate the performance limits and potentials of seismic miner detection and location systems, further investigations are still required to characterize the following items in a more quantitative manner:

- Seismic signals from sources available to miners.
- Seismic noise in coal mine regions.
- Seismic propagation attributes of coal mine overburdens.

These investigations will be largely based on experimental work in the field.* Several of these are described in more detail in the body of this Volume.

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* Selected improvements in the seismic system hardware have since been made by PMSRC, and experimental investigations related to the above three areas have been conducted by Continental Oil Co. for the Bureau of Mines under Contract H0133112.

Table 6

EXPECTED IMPACT OF INVESTMENTS
ON SYSTEM PERFORMANCE AND COST

IMPACT of ↓ on →	Improving Overall Performance	Increasing Overall Cost
. Truly Fieldable Hardware	High	Low
. Trained Experienced Field Crews	High	Moderate
. Site Pre-Calibration Preparation*	High	High
. Improved Seismic Earth Models*	High	Low
. Conventional S/N Enhancement Methods	High	Low
. Sophisticated S/N Enhancement Methods	Low	High
. Controlling Site Man-Made Noise	High	Low

* Applicable mainly to miner location, as opposed to miner detection and location.